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LOW-THRUST ORBIT TRANSFER DESIGN FOR DAWN OPERATIONS AT VESTA

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Upon arrival at the asteroid Vesta, scheduled for July of 2011, the Dawn spacecraft will target a series of four distinct mapping orbits, each providing a unique opportunity to observe Vesta. The unknown, and potentially complex, Vesta gravity field presents challenges for designing low-thrust transfers between these mapping orbits while maintaining spacecraft safety from Vesta occultation of the Sun. This paper provides a description of the orbit transfers designed for Vesta operations along with a discussion of the constraints and methods used to design these transfers. The effect of alternate gravity fields on the viability of the designs and the design method is also considered.

INTRODUCTION

In July of 2011 the Dawn spacecraft is scheduled to begin a year of orbital operations at Vesta, the 2nd most massive main-belt asteroid. Dawn is a NASA Discovery mission that uses solar-electric low-thrust ion propulsion for both interplanetary cruise and orbital operations about its two targets – Vesta and Ceres. During its mission, the Dawn spacecraft will orbit both bodies and perform a series of observations. Vesta and Ceres are protoplanets whose formation is thought to have been interrupted by the formation and presence of Jupiter[1]. With apparently different compositions, observations of Vesta and Ceres are designed to provide a complimentary understanding of the conditions and processes present during the formation of the solar system[1].

Dawn launched in 2007 and, after an initial checkout period[2], began thrusting to achieve a successful Mars gravity assist in February of 2009, and subsequently toward rendezvous with Vesta. At Vesta, the Dawn spacecraft will target a series of four distinct polar mapping orbits (shown in Figure 1), each providing a unique opportunity to observe the asteroid.

Dawn carries two spectrometers, the Visible and Infrared Mapping Spectrometer (VIR), and the Gamma Ray and Neutron Detector (GRaND)[3,4], which will be used to determine Vesta's surface mineralogy and detect key elements that will give insight into Vesta's formation[5]. The spacecraft's Framing Camera will be employed to obtain mapping images to develop visual and topographical maps of Vesta[5] in addition to obtaining optical navigation images. Finally, the determination of Vesta's gravity field will also improve understanding of Vesta's internal structure and formation.

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The first and highest Vesta science orbit is Survey, at 3000 km radius from Vesta. Survey offers the opportunity to obtain spectral imaging from VIR, but lower altitude orbits are needed to obtain higher resolution mapping data. The second mapping orbit is the High Altitude Mapping Orbit (HAMO), at 950 km radius from Vesta. At HAMO altitude, the Framing Camera will be used to perform visual and topographical mapping[5]. HAMO is followed by the Low Altitude Mapping Orbit (LAMO), at 460 km radius from Vesta, the lowest planned orbit at Vesta. The LAMO altitude enables the acquisition of GRaND data while providing high resolution determination of Vesta's gravity field[5]. The final mapping orbit is the High Altitude Mapping Orbit 2 (HAMO-2), which has many of the same characteristics as HAMO, including altitude and science objectives. Due to the timing in the mission, HAMO-2 offers improved lighting conditions for observations of northern latitudes not possible during HAMO.

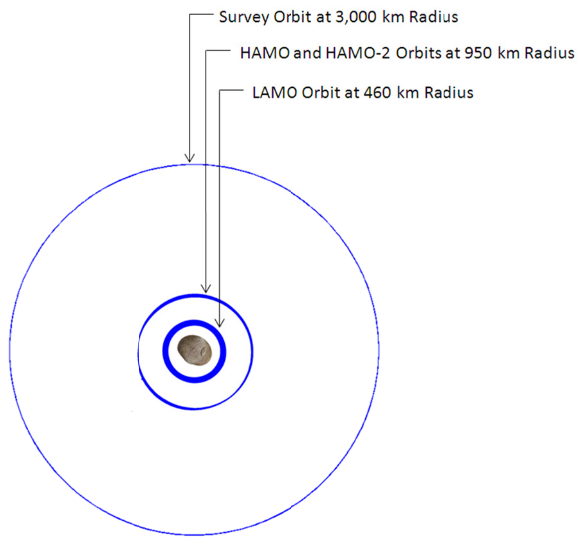


Figure 1 - Vesta Science Orbits

This paper provides a description of the orbit transfers targeting these four mapping orbits along with a discussion of the constraints and methods used to design those transfers. The unknown and potentially complex Vesta gravity field presents many challenges for the design of low-thrust transfers between these mapping orbits. This task is further complicated by the spacecraft safety requirement that Dawn maintain line-of-sight to the Sun at all times during the nominal mission, and for a minimum of 25 days in the event of an anomaly resulting in a thrusting outage. This spacecraft safety requirement proves particularly challenging for the LAMO to HAMO2 transfer design.

PROCESS

To support this analysis, Mystic, a Static Dynamic Optimal Control Algorithm developed by Gregory Whiffen[6,7,8], was used to find locally mass-optimal low-thrust orbit transfers around a number of potential gravity fields. Two Vesta gravity models, developed by Alex Konopliv at the Jet Propulsion Laboratory, were used for the analysis presented. The primary gravity field used is an 8x8 uniform-density model of Vesta based on a Vesta shape model[9], and gravitational parameter of 17.8 km^3/s^2. The 2nd gravity model used is a 15x15 field that assumes a spherical core, 150 km in radius, with density twice that of the mantle with the same 17.8 km^3/s^2 gravitational parameter. The uniform density gravity model, with its strong gravitational harmonics, was intended to be a conservatively challenging gravity field for transfer design and orbit stability. The core-based gravity field was selected as a higher-likelihood gravity field whose weaker gravity harmonics would offer a presumably less challenging, but more representative trajectory design.

For this analysis, the Dawn spacecraft characteristics (see Spacecraft Power in the Appendix) and thruster performance (see Thrust and Massflow in the Appendix) were used. See Reference 10 for additional discussion of Dawn spacecraft characteristics.

VESTA MAPPING ORBITS

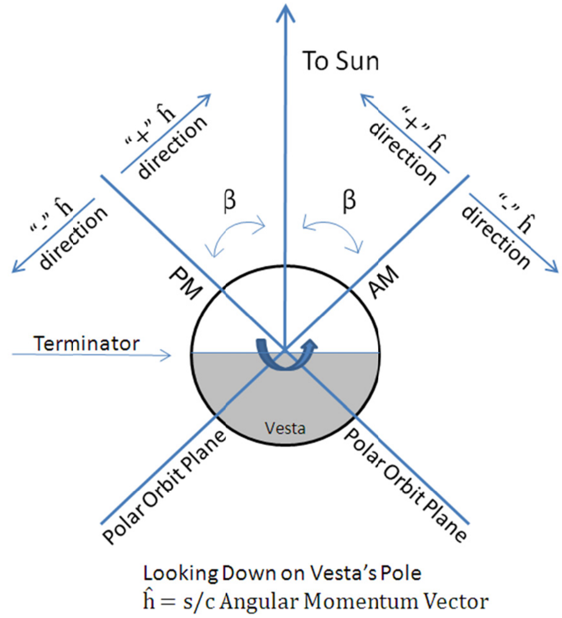
Four mapping orbits are planned at Vesta at three different orbital altitudes, all at or near polar inclination. Each orbit starts instantaneously circular but has growing eccentricity resulting from the Vesta gravity model. The following sections introduce the four mapping orbits. The first and highest-altitude mapping orbit is Survey.

Survey

The Survey mapping orbit (see Figure 1) has a target radius of 3000 km, but Vesta's gravity field may cause growing oscillations in radius. The Dawn project's baseline gravity field, the uniform-density model described earlier, results in deviations in radius of up to 5 km by the end of Survey. Survey is 6 orbits in duration, corresponding to 17 days for the modeled gravitational parameter.

Survey orbit has no groundtrack requirement, but requires an initial Sun-β angle of 10^o. The β angle is the angle between the orbit plane and the Vesta-Sun line as illustrated in Figure 2. The 10^o target provides desired lighting conditions for VIR observations while avoiding entering Vesta's shadow. A 3000 km circular polar orbit with a 10^o β angle could describe any of four possible orbit planes. Two of these orbits cross the lit-side equator on the morning (AM) side of the Vesta-Sun line (see the AM polar orbit plane in Figure 2), one with the Vesta-Sun component of the angular momentum vector pointed toward the Sun (+) and one pointed away (-). The two other orbits cross on the evening (PM) side (see Figure 2). The four combinations are referred to as +AM, -AM, +PM and -PM.

The orientation selected for Survey orbit is +AM. The β angle naturally drifts due to Vesta's motion about the Sun. The AM selection of the orbit causes the natural β angle drift to be positive, increasing the β angle. This is a desirable feature given that orbits with low β angles enter Vesta's shadow. Since Dawn is a solar powered spacecraft, entering Vesta's shadow has been identified as a potential risk to spacecraft systems health, prompting a flight rule against entering shadow throughout the Vesta mission. The positive β angle drift during Survey leads to a final β angle of 15.4^o.



Iomentum

The selection of a +AM, polar, circular orbit with a 10^o initial β angle fully defines the orbit plane and rotational direction of Survey. There is no requirement for the initial phase of the orbit. This flexibility in the initial phase of Survey reduces the amount of statistical thrusting required to achieve Survey orbit[11].

High Altitude Mapping Obit

The Vesta High Altitude Mapping Orbit (HAMO), shown in Figure 3, has a target radius between 925 and 975 km and a duration of 60 orbits at a 12.3 hour orbital period. The HAMO groundtrack repeats every 10 orbits with nearly evenly-spaced equator crossings. Figure 4 is an illustration of the groundtrack for the first 10-orbit cycle of the HAMO design shown in Figure 3. The groundtrack requirement implies that Vesta must rotate an integer number of times during the 10-orbit cycle. This relationship dictates the 12.3 hour orbital period, a value which therefore depends on the determination of Vesta's rotational rate. During the repeating groundtrack cycle, each equator crossing must be spaced no greater than 42^o longitude from the nearest equator crossing, with evenly-spaced 36^o crossings being the goal. The uniform-density Vesta gravity model makes evenly spaced equator crossings impossible to be achieved without maneuvers. The HAMO design shown in Figure 4 has a maximum spacing of 37.5^o between equator crossings. Equator crossings spaced as evenly as possible offer the best chance to return uninterrupted mapping images of the entire lit surface.

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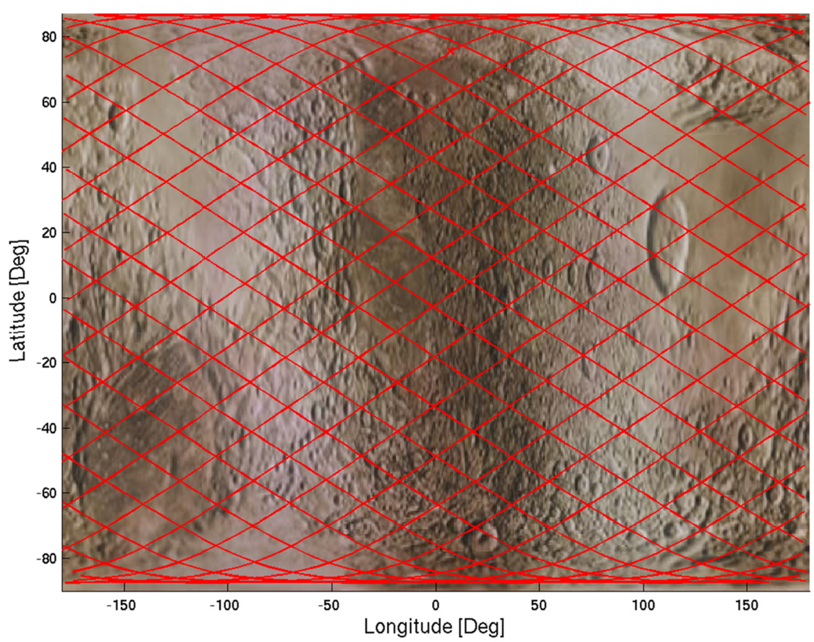
In addition to the groundtrack requirements, HAMO also has a β angle target of 30° with no drift throughout the orbit. Achieving this frozen β angle requires a slightly off-polar inclination determined by the assumed gravity field (92.65° for the groundtrack shown in Figure 4). The frozen β angle offers consistent illumination throughout HAMO imaging.



Low Altitude Mapping Orbit

After HAMO, the Dawn spacecraft will transfer to the Low Altitude Mapping Orbit (LAMO), the lowest mapping orbit during Vesta operations. Due to its low radius, LAMO is particularly susceptible to perturbations in orbit characteristics. A separate stability study[12] was performed to find a LAMO with a frozen β angle resilient to perturbations. This study will be repeated during HAMO when Vesta's gravity field is better understood. Currently, the stability study has identified the LAMO orbit shown in Figure 5, which has a radius of approximately 460 km from Vesta (ranging between 405 and 521 km radius based on the uniform-density Vesta gravity field).

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Once Vesta's gravity field is well determined, finding a stable LAMO will be a critical operation at Vesta. LAMO is the longest mapping orbit at 70 days in nominal duration, plus an extended duration designed to use all extra available time at Vesta. Current estimates of the potential duration of LAMO are as much as 120 days[*]. The frozen LAMO β angle target is 45°, very near the 39° β angle at which shadow occurs at that orbital radius[†]. Because entering shadow is an unacceptable scenario for the mission, LAMO, the longest and most dynamic of the mapping orbits, is also the most dangerous of the mapping orbits for spacecraft health.

Optimal lighting conditions occur at LAMO β angles lower than 45°, and thus the 45° β angle target is a compromise between spacecraft safety and science objectives. Also, LAMO is the only mapping orbit to have planned Orbit Maintenance Maneuvers (OMMs). This, again, is a function of spacecraft safety rather than science objectives, since thrusting is generally incompatible with performing science observations and data transfers. LAMO orbit maintenance maneuvers will occur each week to correct perturbations and thereby prevent the spacecraft from nearing eclipse[12].

In addition to the above requirements, LAMO's groundtrack requirements are designed to achieve global groundtrack coverage in the first 60 days, with a maximum of 6° longitudinal

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[*] Estimates of available time at Vesta use current spacecraft power, thruster, and mass estimates to project the earliest possible arrival at Survey orbit and latest possible departure from Vesta. The 120-day LAMO also assumes that no future anomalous scenarios, or design changes reduce the time available for Vesta science.

[†] Shadow occurring at 39° is based on a Vesta shape model with a spherical 265 km radius. More detailed shape models indicate that shadow can occur at higher β angles than 39°.

spacing in equator crossings during that time. The global coverage with closely spaced equator crossings is designed to maximize surface coverage for GRaND.

High Altitude Mapping Orbit 2

After LAMO, the Dawn spacecraft will enter its final mapping orbit at Vesta, the High Altitude Mapping Orbit 2 (HAMO-2). The HAMO-2 characteristics are very similar to HAMO, including the 950 km radius and the repeating groundtrack (see Figure 4), but the orbit is designed to occur as late as possible in the mission to achieve the most favorable lighting conditions. The main difference between HAMO-2 and HAMO is the β angle target, which is 30^{o} for HAMO and 45^{o} for HAMO-2. Again, a β angle lower than 45^{o} would be preferable to optimize lighting conditions. However, in this case, it was the duration of the transfer that required the β angle to be raised, since achieving a lower β angle required extensive flight time, as discussed in further detail below.

ORBIT TRANSFERS AT VESTA

Approach to Survey Transfer

Survey is targeted by a “transfer” referred to as “Approach”, which is the transition from interplanetary cruise, through capture at Vesta, to Survey. The start of Approach, 97 days before the start of Survey, was selected to correspond with the first optical navigation observation of Vesta. At the start of the Approach, the spacecraft will be approximately 1.2 million km from Vesta, a distance that enables the optical navigation team to begin collecting useable data. An example trajectory capturing the final 29 days of Vesta Approach is shown in Figure 6.

Thrusting during interplanetary cruise and Approach is designed to arrive at Survey in the minimum possible time. During the 97 days of Approach, 67 days are spent thrusting, always at the maximum thrust capability allowed by the available power. Of the remaining 30 days of Approach, 22.5 days are spent performing navigation, science, and systems data collection and transmission[*]. These activities require the spacecraft to point to a particular orientation to obtain or transmit data, which is generally incompatible with thrusting.

In addition to thrusting, obtaining and transmitting data, 7.5 days throughout the Approach schedule are reserved for 10 Maneuver Expansion Periods (MEPs). MEP’s are coasting blocks in the design trajectory that will be available for statistical thrusting during operations. Since the design trajectory represents an optimal minimum-time trajectory to Vesta, any statistical deviations would result in late arrival to Survey. MEP’s are therefore needed to provide control authority to correct for statistical deviations while preserving the target Survey arrival date. These MEPs are placed and sized according to the results of Monte Carlo analyses of the statistical perturbations that will occur during Approach operations[11]. MEPs are used in this manner for all transfers to science orbits.

In addition to matching Vesta’s orbital phase, a main goal of Approach thrusting is to raise the spacecraft aphelion to match Vesta. As aphelion is raised, the Dawn spacecraft progresses toward Vesta, until capture (zero orbital energy with respect to Vesta) occurs. At capture, less than 8.8 days of thrusting remain before Survey orbit is achieved, yet Approach thrust vectors still contain a significant out-of-plane component intended to align the orbit plane with the targeted Survey

[*] These activities include performing radiometric tracking of the spacecraft, collecting optical navigation images, collecting rotational characterization images, performing science instrument calibrations and communicating the results of those calibrations, as well as communicating any additional spacecraft systems or instrument telemetry to the ground.

orbit. Even at only 3.5 days of thrusting prior to Survey, inclination is still 2° from the target, and β angle is over 4° from the target*.

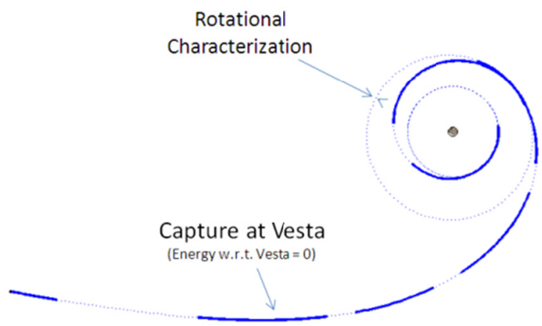


Figure 6 - Trajectory Plot of the Final 29 days of Approach-to-Survey Transfer about a Uniform-Density Vesta (Bold Indicates Thrusting)

Approach to Survey is the only transfer that contains an intermediate orbit target for the purposes of Vesta observation. Approximately 17 days prior to Survey, only 3.5 of which are spent thrusting, an activity is planned to characterize Vesta's rotation and orientation. This rotational characterization activity involves multiple observations during a 3.6 day window, and requires its own targeting to place a Vesta equator and south pole crossing at the desired locations within that window. Thus a suitable Approach to Survey transfer must target this intermediate state in addition to the final target at the start of Survey. Characterization of Vesta's orientation during approach is critical to achieving an accurate delivery to the polar Survey orbit. This rotational characterization is the final, most accurate determination of Vesta's orientation prior to Survey.

With a rough initial guess that simply gets close to but does not capture at Vesta, the Mystic trajectory optimization software can determine an optimal thrust profile that achieves the Survey constraints on β angle, inclination, radius, and eccentricity. Once an optimal trajectory to Survey is computed, additional constraints during Approach are added to achieve the intermediate equator crossing, altitude, and eccentricity required for the 3.6-day rotational characterization activity.

Survey to High Altitude Mapping Orbit Transfer

The Survey to HAMO transfer takes place over 28 days, including 11.7 days of thrusting, 2.3 days reserved for MEPs, 1.2 days for a purely statistical Trajectory Correction Maneuver (TCM) to improve HAMO delivery accuracy, 9.5 days performing navigation, science, and systems data collection and transmission, and 0.3 days of optimal coasting† throughout the transfer. In addition to these activities, there is also a 3-day "Quiet Period". A "Quiet Period" is a coasting block in the trajectory that is present for the sole purpose of giving the ground personnel the opportunity to design a new thrusting sequence while the spacecraft is not thrusting. This procedure improves the delivery accuracy of the maneuver being designed since the spacecraft is coasting and thus

* With 3.5 days of thrust remaining, the "target" is the β angle that would ballistically achieve a 10 degree β angle at the start of Survey..

† Optimal coasting for this trajectory is an artifact of the scheduling process involving the navigation, spacecraft, and science teams, and is likely to exist during operations.

maneuver execution errors are not accumulating during the design. An example Survey to HAMO transfer is shown in Figure 7, containing 37 revolutions about Vesta.

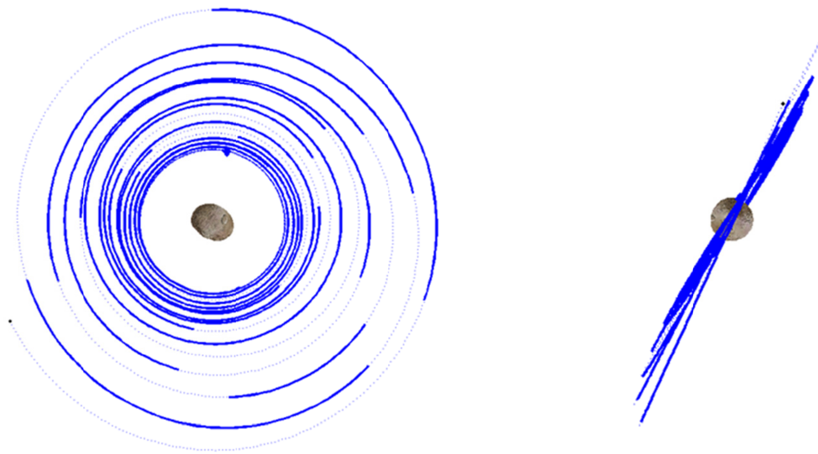
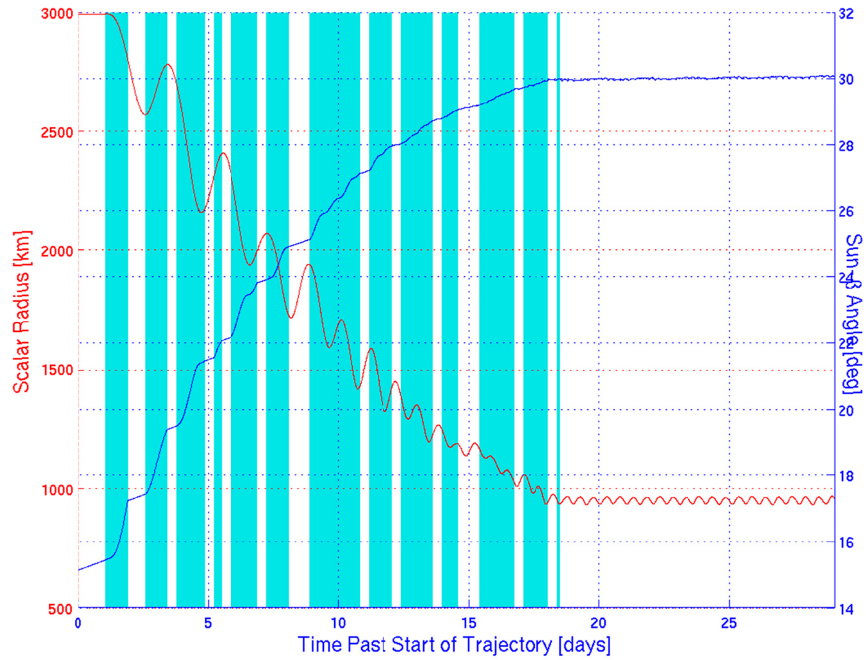


Figure 7 - Trajectory Views of 28-day Survey to High Altitude Mapping Orbit Transfer about a Uniform Density Vesta (Bold Indicates Thrusting)

During the Survey to HAMO transfer, the Dawn spacecraft will not only perform an altitude change, but a plane change as well to increase the β angle from 15.4^{o} at the end of Survey to 30^{o} at the start of HAMO, an increase of 14.6^{o}. However, the natural β angle progression due to Vesta's orbit about the Sun provides a portion of this β angle increase, assisting in the transfer. Specifically, the natural beta angle increase in Survey would be 5.1^{o} by the end of the deterministic thrusting for the transfer*. Thus, the required change in β angle -- beyond that which could be achieved ballistically by remaining in Survey -- is 9.5^{o}. Additionally, during the transfer, inclination must be increased from 90^{o} to 92.65^{o} to achieve a frozen β angle throughout HAMO. A plot of β angle and orbital radius throughout the transfer is shown in Figure 8. Note that, as a result of coasting activities for statistical thrusting and science activities, the final 10.5 days of the transfer do not include any design thrusting.

* The β angle would increase by 5.1^{o} without thrusting; however, thrusting during the transfer increases the inclination, which reduces the natural β angle drift, in order to achieve a frozen β angle by the end of the transfer. Thus, the drift in β angle due to Vesta's motion about the Sun during the transfer will be less than 5.1^{o}.



β Angle

The Mystic optimizer was used to determine an optimal Survey to HAMO transfer. Mystic was provided with an initial guess consisting of a simple anti-velocity thrust profile to spiral in toward the target HAMO radius. The optimizer was given the targets necessary to successfully achieve HAMO, including circular eccentricity, 92.65° inclination[*], 30° β angle, and a nearly 12-hour orbital period (to provide the required HAMO groundtrack). The Survey to HAMO optimization problem was solved as a fixed-time trajectory with a minimum-propellant optimization objective. Because of the high number of revolutions in the solution, the minimum-propellant objective was very weakly affected by the placement of optimal coasting arcs. As a result, Mystic spent significant computational time to optimize the placement of these coasting arcs, thus, significant optimal coasting adversely affected computation time. This effect was mitigated by the desire to minimize transfer time and hence minimize optimal coasting. The result of the Mystic optimization is the Survey to HAMO transfer shown in Figure 7.

High Altitude Mapping Orbit to Low Altitude Mapping Orbit Transfer

The HAMO to LAMO transfer takes place over a total of 38.5 days, including 11.2 days of thrusting, 8 days reserved for MEPs, 2.5 days for two TCMs to improve delivery accuracy[11], 7.2 days performing navigation, science, and systems data collection and transmission, and 6 days for

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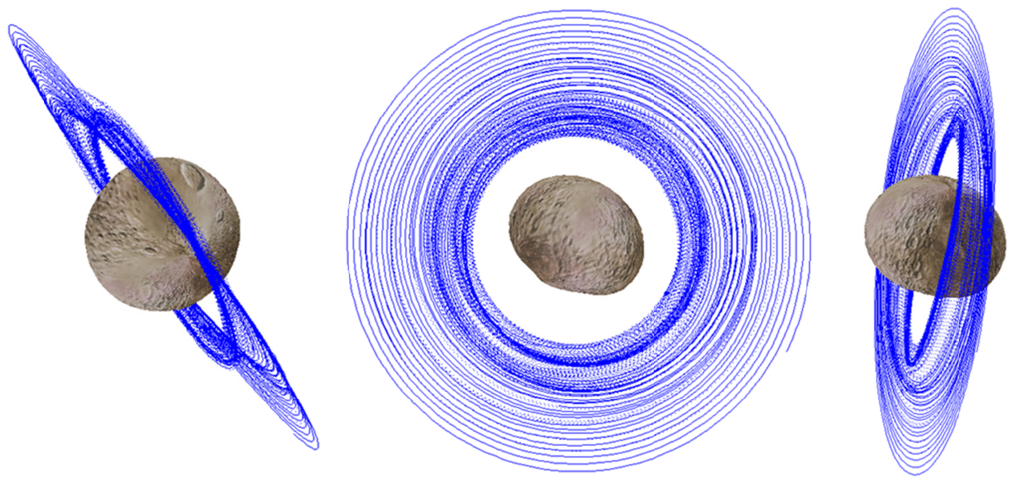
[*] The inclination required to achieve a frozen β angle is determined by Vesta's gravity field (particularly J2), which is used to counteract the β angle increase caused by Vesta's motion about the Sun. Therefore, the final HAMO inclination will be a product of the determination of Vesta's gravity field.

three Quiet Periods. The remaining 3.6 days represent optimal coasting periods during which thrusting is less efficient and not required to accomplish the transfer in the flight time allocated. The example HAMO to LAMO transfer shown in Figure 9 contains 170 revolutions about Vesta. HAMO ends at 30^{o} β angle and 92.65^{o} inclination, and LAMO begins at 45^{o} β angle and 90^{o} inclination. Thus the transfer performs a 15^{o} increase in β angle, and over 2^{o} change in inclination. As a result of the final MEP, Quiet Period, TCM, and science and navigation activity prior to LAMO, the final 6 days of the transfer cannot include any deterministic thrusting*. A time-history of β angle and orbital radius throughout the transfer is shown in Figure 10, and inclination is shown in Figure 11.



To transfer from HAMO radius at 950 km to LAMO radius at 460 km, the spacecraft must pass through the 1:1 resonance of Vesta's rotational motion with the spacecraft's orbital period. At this resonance, the spacecraft experiences the same orientation of Vesta's gravity field at each point in its orbit from one orbit to the next, resulting in strong gravitational perturbations† for gravity fields including tesseral and sectoral harmonic terms[14]. This resonance presents a trajectory design and navigational challenge, but it also represents an opportunity to take advantage of gravitational perturbations to save time and propellant in achieving the necessary orbital plane change between HAMO and LAMO. With a gravitational parameter of $17.8 km^3/s^2$ and modeling Vesta's gravity as a point-mass, the 1:1 resonance would occur at a circular orbital radius of 550 km. However, due to orbital perturbations caused by the uniform-density gravity field, the resonance occupies an area between 500 and 600 km orbital radius as illustrated in Figure 10. The example HAMO to LAMO transfer utilizes this resonance to accomplish approximately 10 de-

* Optimal coasting also takes place at the end of the transfer, causing deterministic thrusting to end over 7 days prior to the start of LAMO.

† Other resonances between the spacecraft's orbital period and Vesta's rotational rate must also be traversed during orbit transfers. Each of the resonances has a similar effect, but the 1:1 resonance is by far the strongest of the resonances, and is the only one that played a significant role in the transfer design process.

grees of the required β angle plane change by coasting inside the resonance until the majority of the plane change is accomplished.

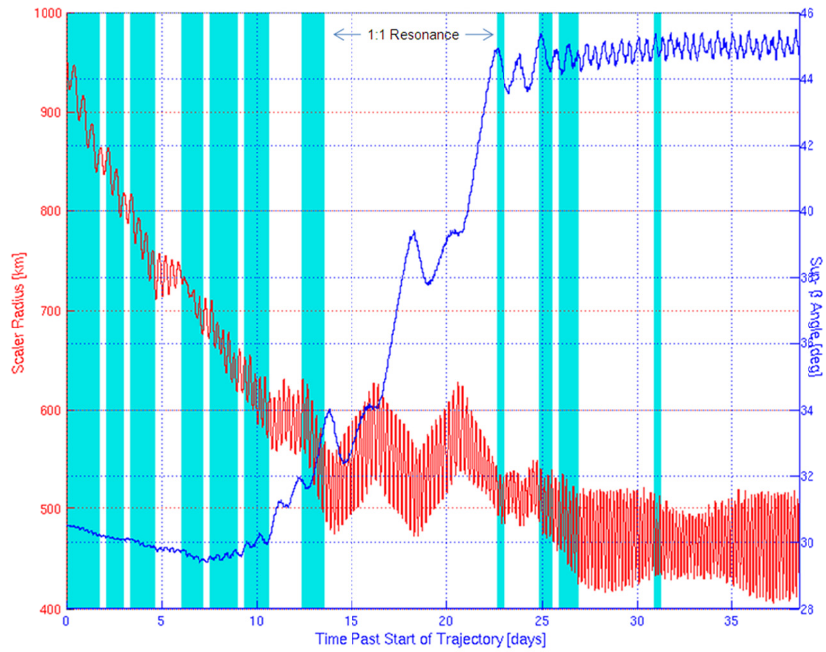


Figure 10 - HAMO to LAMO Orbit Transfer Instantaneous Scalar Radius and Sun β Angle with Respect to Vesta versus Flight Time (Shaded Regions Indicate Thrusting)

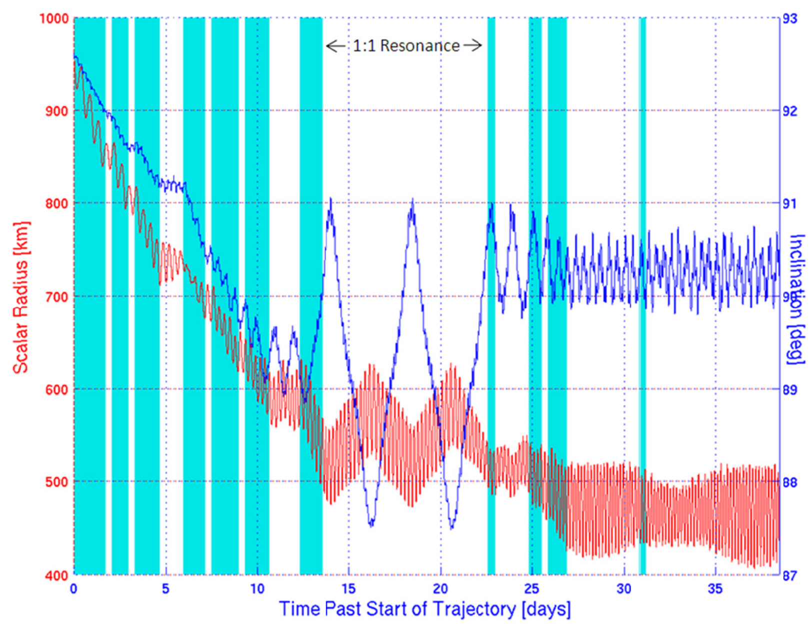
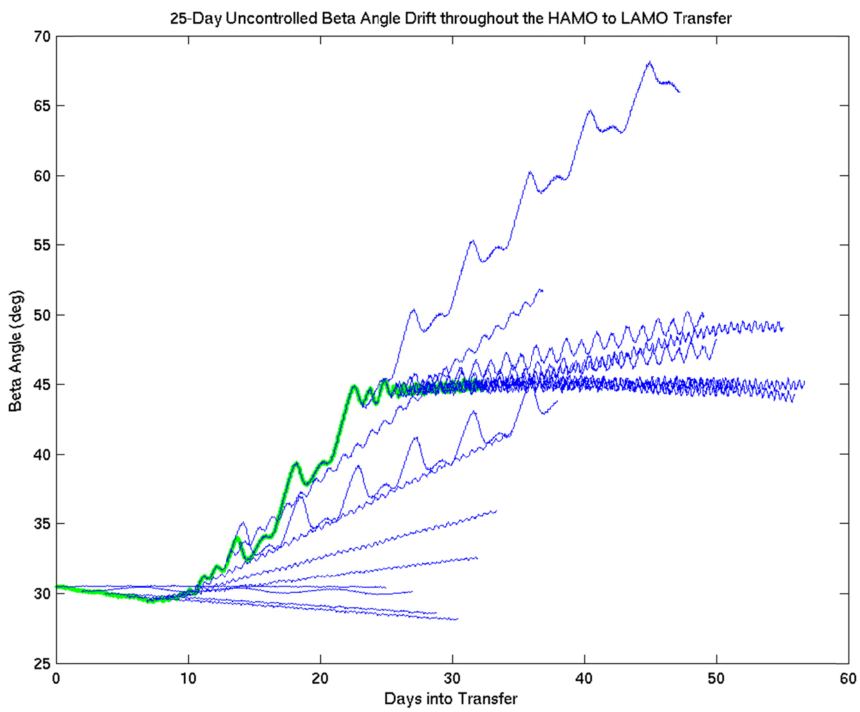


Figure 11 - HAMO to LAMO Orbit Transfer Instantaneous Scalar Radius and Inclination with Respect to Vesta versus Flight Time (Shaded Regions Indicate Thrusting)

A key challenge in designing the Vesta HAMO to LAMO transfer is accounting for the effect of alternate gravity fields on the transfer duration and dynamics. So far, we have discussed transfers based only on the uniform-density shape-based gravity field, a field that was selected not as a likely scenario, but as a challenging gravity field due to its strong harmonics.

Another gravity field investigated was a Vesta with a dense core, but with an identical gravitational parameter as the uniform-density gravity field (described earlier). The resulting reduction in gravity harmonics makes the 1:1 resonance a less dynamic environment - reducing design and navigation complexity, but simultaneously reducing the plane change achieved while passing through the resonance. For a HAMO to LAMO transfer based on the dense-core gravity field, the 1:1 resonance accounted for less than 3^{o} β angle change. Greater β angle changes could have been achieved by lingering longer in the resonance, but this increased flight times to LAMO. As a result, the dense-core gravity field required an additional 1.5 days of thrusting throughout the transfer compared to the uniform density gravity model. This additional thrusting represents a minimum threshold of additional thrusting capability to be required of any transfers designed in the uniform-density gravity field, since the advantages of strong gravity harmonics cannot be guaranteed for all possible gravity models. Trajectories that rely on the resonance to perform time-efficient plane changes can be infeasible for gravity fields with reduced harmonics[14].



rift.

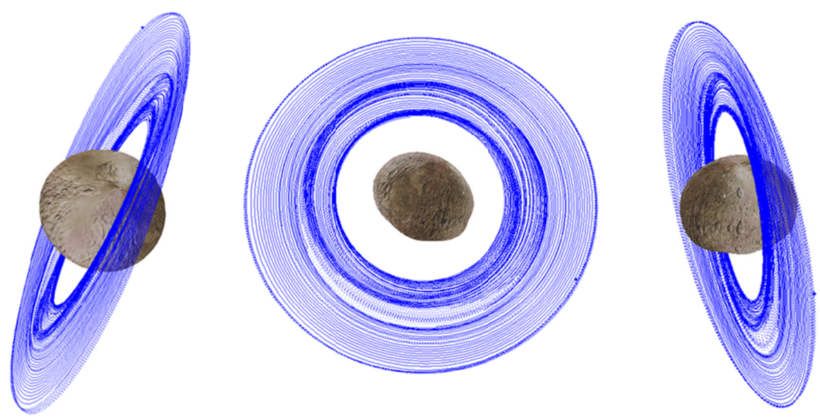
As previously mentioned, the Dawn project requires that transfers avoid Vesta occultations of the Sun at all times and also that in the event of an anomalous thrusting outage at any point during the transfer, the resulting ballistic trajectory must also avoid solar occultation for a minimum of 25 days. To verify that this requirement was met by the HAMO to LAMO transfer, β angle was calculated for ballistic propagations of states sampled throughout the transfer. Figure 12 shows a 25 day uncontrolled evolution of β angle sampled throughout the transfer of Figure 9.

None of the propagated ballistic trajectories in Figure 12 passed into shadow within the 25 day period.

To ensure controllability during the transfer and identify portions of the transfer particularly susceptible to perturbations, a powered-flight stability analysis[13] was performed on this transfer. Regions of the transfer particularly sensitive to perturbations and the methods planned for navigating these regions are discussed elsewhere in greater detail[11].

Low Altitude Mapping Orbit to High Altitude Mapping Orbit 2 Transfer

The LAMO to HAMO-2 transfer takes place over a total of 42 days, including 14 days of thrusting, 7 days reserved for MEPs, 1 day for a purely statistical TCM near HAMO-2, 11 days performing navigation, science, and systems data collection and transmission, and 6 days for 2 Quiet Periods. The remaining 3 days represent optimal coasting periods during which thrusting is less efficient and not required to accomplish the transfer in the flight time allocated. The example LAMO to HAMO-2 transfer shown in Figure 13 contains 138 revolutions about Vesta. LAMO ends below 45° β angle (near 43°) and just above 90° inclination, requiring the transfer to increase the β angle 2° to HAMO-2 and perform over 2° change in inclination back to 92.65° to deliver to a frozen β angle in HAMO-2.



sity Vesta

As in the HAMO to LAMO transfer, the LAMO to HAMO-2 transfer must pass through the strong 1:1 resonance as the orbit is raised to HAMO-2 altitude. However for this transfer, unlike the HAMO to LAMO transfer, the initial and final β angles are similar. As illustrated in Figure 14 and Figure 15, the mass-optimal transfer from LAMO to HAMO-2 through the 1:1 resonance fails the 25 day uncontrolled β angle safety test. Entry into Vesta's shadow is indicated in Figure 15 in red. The optimizer decreased the β angle both before and after passing through the resonance to counteract the increase in β angle through the resonance*. The portions of the transfer

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* An alternative solution to this problem, where the 1:1 resonance is used to decrease the β angle rather than increase it, and thrusting is used to increase β angle rather than decrease it, likely also exists. This solution was not pursued because it had the undesirable characteristic of using the resonance to impart a rapid decrease in β angle, making it unlikely to satisfy spacecraft safety requirements on uncontrolled β angle.

with decreasing β angle instantaneously placed the spacecraft on a trajectory that, when propagated ballistically, eventually enter Vesta's shadow. Due to the plane change imparted by the 1:1 resonance, it was numerically optimal to thrust at all times while passing through the resonance to minimize the resulting plane change. This thrusting is in sharp contrast to the LAMO to HAMO transfer where a significant amount of optimal coasting appeared as the spacecraft lingered in the resonance to benefit from the plane change.

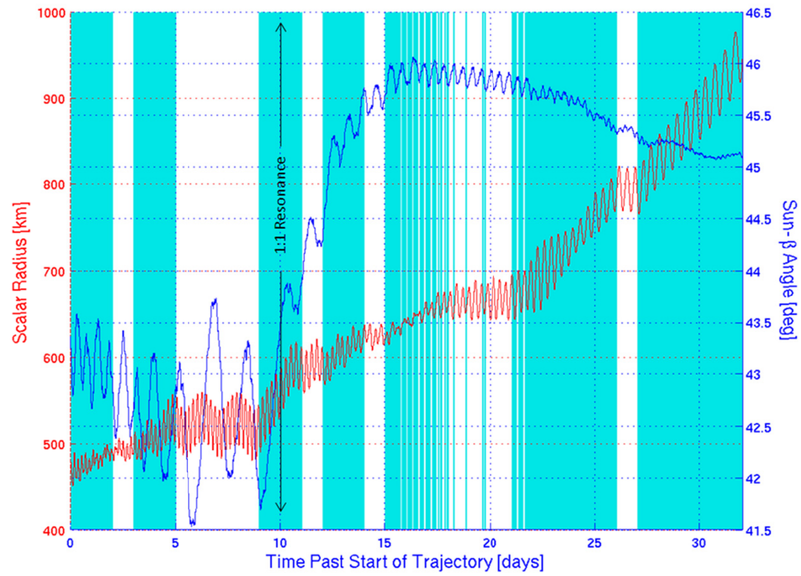


Figure 14 - LAMO to HAMO-2 Unconstrained Orbit Transfer Instantaneous Scalar Radius and Sun-β Angle as a Function of Flight Time (Shaded Regions Indicate Thrusting)

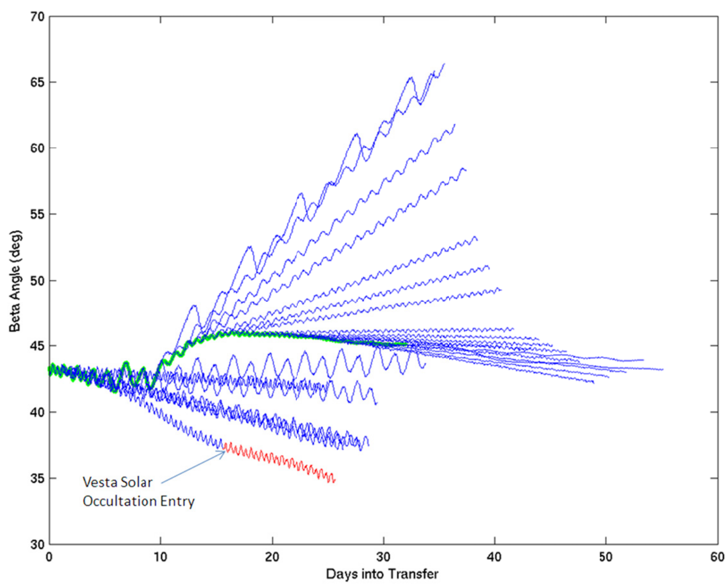
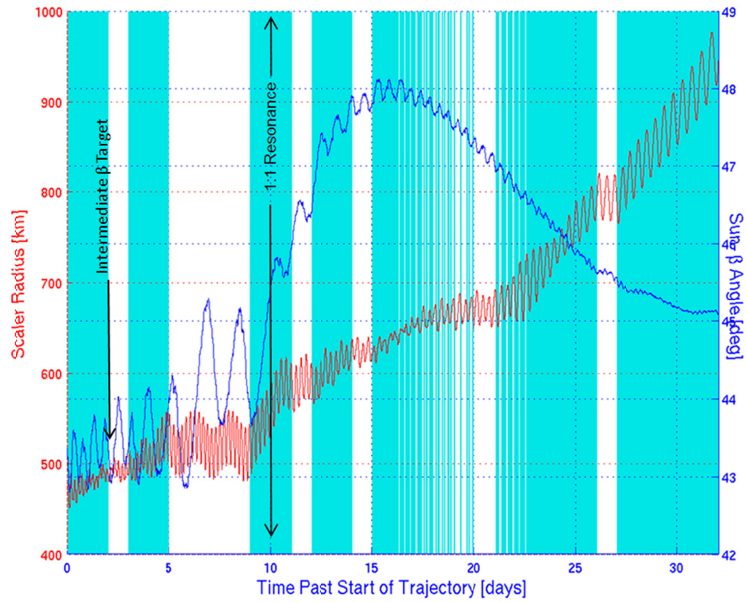


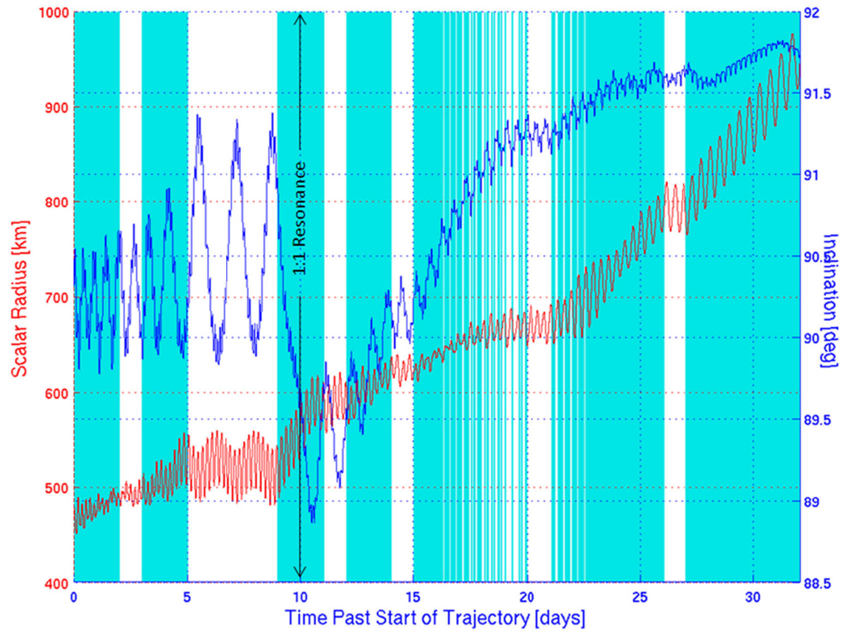
Figure 15 – Unconstrained LAMO to HAMO-2 25-Day Uncontrolled Beta Angle Drift. Design Trajectory in Green, Ballistic Trajectories in Blue

To avoid placing the spacecraft in unsafe states, the transfer was constrained with an intermediate β angle target applied before the resonance to raise the instantaneous β angle. This intermediate target results in additional thrusting both before and after the resonance. Figure 16 and Figure 17 show the resulting transfer. The additional thrusting results in the trajectory design satisfying spacecraft safety requirements throughout the transfer as shown in Figure 18.



Analyses of more centralized gravity fields for the LAMO to HAMO-2 transfer have not been completed, but, unlike the HAMO to LAMO transfer, a reduction in gravity harmonics is expected to benefit the LAMO to HAMO-2 transfer as the β angle change due to the resonance will be less pronounced, and therefore easier to accommodate.

An early design for HAMO-2 included a 32^{o} β angle target, more closely resembling HAMO than the current 45^{o} target. Reaching a 32^{o} target required substantially reducing the β angle throughout the transfer. The 1:1 resonance could be employed to efficiently accomplish this plane change, but, as illustrated above, even a slightly negative β angle trend at low altitude, if left uncontrolled, can cause the spacecraft to quickly enter Vesta's shadow. Decreasing the β angle at low altitude is time and propellant-efficient, but violates spacecraft safety requirements. Performing this β angle change at higher altitudes, where safety requirements could be met, substantially increases transfer time. In the cases examined, as much as 28 days of additional transfer time were required to achieve 32^{o} β angle at higher altitude. As a result, the β angle target for HAMO-2 was raised to save transfer time.



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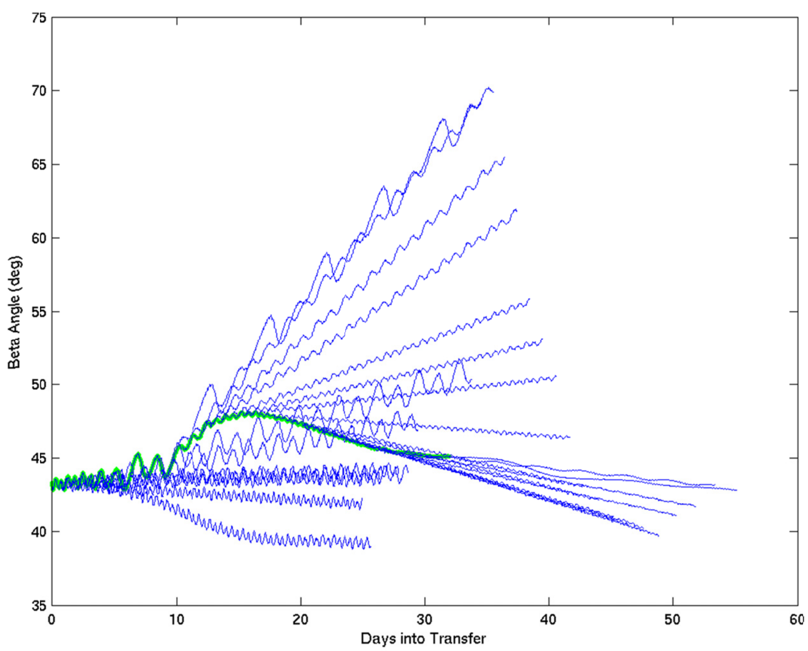

ı Angle

CONCLUSIONS

The Static Dynamic Optimal Control Algorithm, Mystic, was used to generate optimal trajectories in support of Dawn Vesta operations for each of the Vesta science orbit transfers. These transfers were designed to achieve spacecraft safety from occultation of the Sun in the event of an unplanned thrusting outage.

Of the four transfers to science orbits, by far the most complex are the HAMO to LAMO and LAMO to HAMO-2 transfers. Each includes well over 100 orbits about of Vesta and passes through the 1:1 resonance of spacecraft orbital period to Vesta rotation rate. This 1:1 resonance enables strong gravitational perturbations to dramatically alter the spacecraft orbital geometry in a short time period. The resonance can be leveraged to achieve desired plane changes with minimal propellant and flight time, or can be detrimental when such plane changes are undesired.

A 38.3 day HAMO to LAMO transfer about the uniform-density gravity field requires an additional 1.5 days of thrusting when designed for a dense centralized core gravity field due to the weaker gravity harmonics. This effect is most noticeable through the 1:1 resonance where gravity harmonics are heavily utilized by the optimizer to achieve the desired plane change to increase the β angle when transferring from HAMO to LAMO.

The LAMO to HAMO-2 transfer presented many of the same challenges as the HAMO to LAMO transfer, as well as an additional challenge – minimizing the β angle perturbation from the resonance. Accordingly, during this transfer, thrusting is required to counteract the natural β angle change imparted by traveling through the 1:1 resonance. Counteracting the remaining β angle shift from the resonance requires a controlled decrease in β angle – sending the spacecraft toward eclipse. This poses a trajectory design challenge to maintain spacecraft safety in the event of an unplanned thrust outage. A low-altitude intermediate β angle target was employed to encourage the optimizer to avoid utilizing such unsafe spacecraft states.

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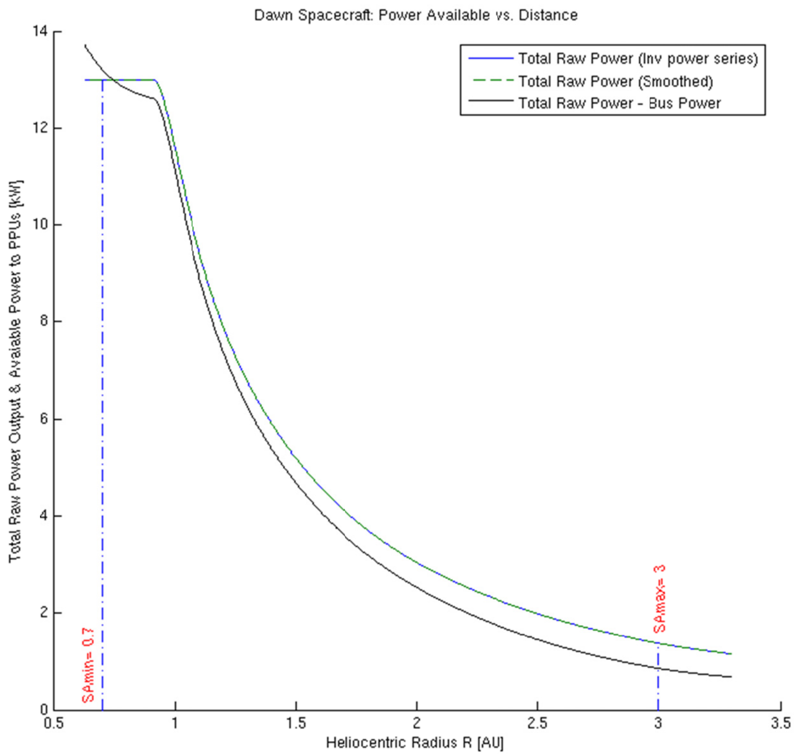
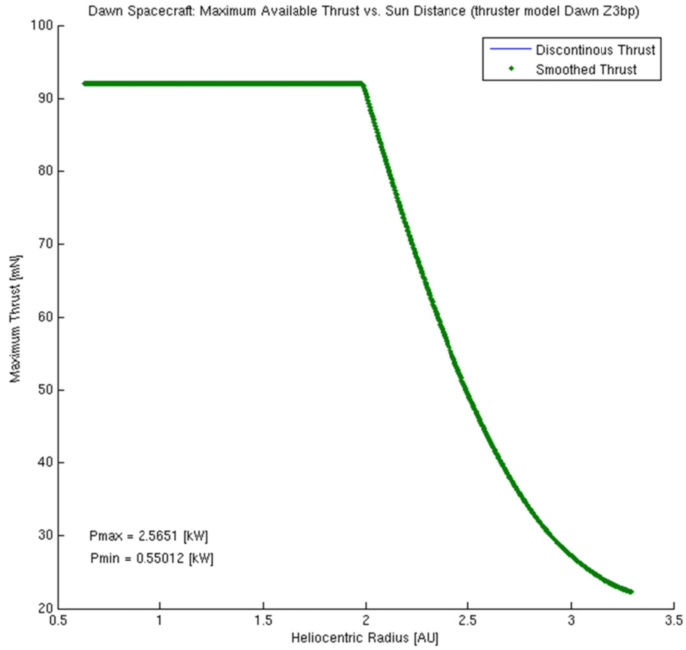
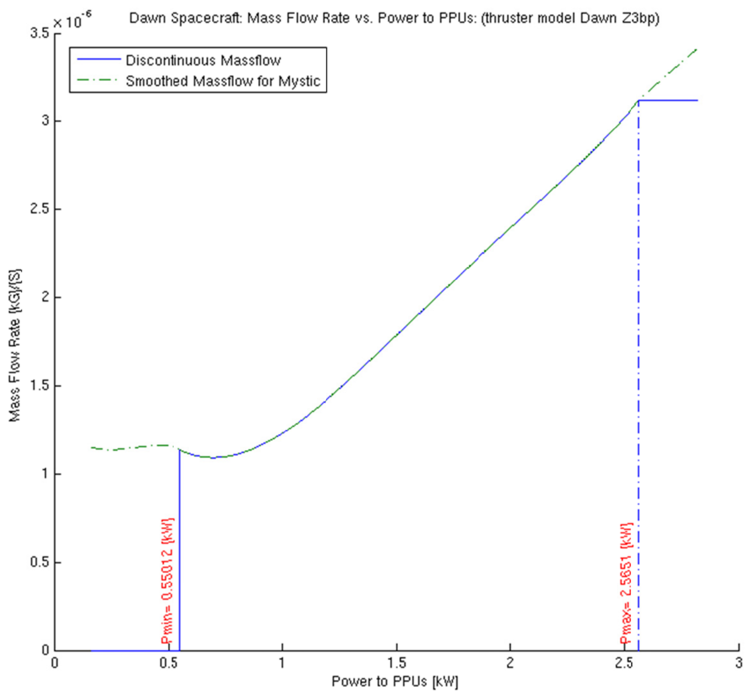
APPENDIX



Dawn Spacecraft Power vs. Heliocentric Distance



Dawn Spacecraft Maximum Thrust vs. Heliocentric Distance



Dawn Spacecraft Thruster Mass Flow vs. Power Available